MEASUREMENTS OF STIFFNESS AND GEOMETRIC COMPATIBILITY IN FRONT-TO-SIDE CRASHES

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Paper Number 349

ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) routinely measures the force exerted on the barrier in crash tests. Thirty-six load cells on the face of the rigid barrier measure the force. This study examines the load cell barrier data collected during recent years of NCAP testing to determine how it can be used to assess vehicle compatibility in vehicle-to-vehicle front-to-side crashes.

The height of the center-of-force measured by the columns of load cells is proposed as a metric for quantitatively describing the geometric properties of the crash forces. For front-to-side crashes, the geometric and stiffness properties of frontal structures during the early stages of crush are applicable. Consequently, geometric and stiffness measurements at a crush of 125 mm are presented in this paper. This paper shows the range of the compatibility and stiffness parameters measured on cars, pickups, vans, and multi-purpose vehicles.

INTRODUCTION

The crash incompatibility between vehicles has been attributed to three vehicle factors: (1) mass incompatibility, (2) stiffness incompatibility, and (3) geometric incompatibility [Gabler, 1998]. The measurement of vehicle mass is relatively straightforward. However, the measurement of stiffness and geometric compatibility needs further definition.

For a stiffness metric, Gabler used the linear stiffness based on the vehicle crush at the maximum barrier force in a 35-mph crash into a rigid barrier. In survivable front-to-side collisions, the frontal crush does not produce the maximum barrier force. Consequently, the stiffness at lower values of crush is more applicable.

The Insurance Institute for Highway Safety reported a series of tests front-to-side crash tests to assess the influence of mass, stiffness, and vehicle ride height [Nolan, 99]. The results were somewhat inconclusive, but suggested that the manner in which the striking vehicle deforms the struck vehicle has more influence than the vehicle stiffness alone. This finding is consistent with earlier observations made by Hobbs [89]. These investigations emphasize the importance of the geometry of the impacting vehicle in addition to its stiffness and mass.

Past studies of compatibility by the authors have addressed primarily front-to-front compatibility [Digges, 98, 99 and 00]. This analysis modifies the approach presented earlier to address front-to-side compatibility. In the past studies the stiffness and geometric characteristics were examined at 250 mm and 375 mm of crush. However, observations of real world crashes suggests that the frontal structural characteristics at lower levels of crush are applicable [Augenstein, 00]. In this study, the vehicle frontal properties at 125 mm of crush are analyzed.

BARRIER INFORMATION

The barrier used in the New Car Assessment Program (NCAP) is a rigid, fixed barrier with 36 force measuring load cells on its surface. The load cell array consists of 4 rows of 9 cells, as shown in Figure 1. The columns are numbered 1 through 9, starting at the left, facing the barrier. The array is subdivided into 6 groupings, 1 through 6, numbered left to right, and beginning with lower left grouping (see Figure 1).

The array of load cells measures the distribution of forces that the vehicle imposes on the barrier during a crash. In this study, the relationship between barrier forces and their geometric location are of particular interest. Consequently, the forces on each row and column of load cells are examined.

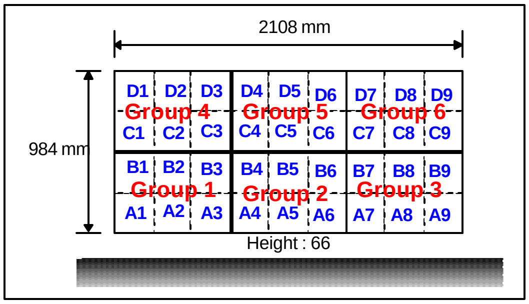

Figure 1. Configuration of Load Cells on Barrier

DATA PROCESSING PROCEDURES

In addition to load cell data, each NCAP test contains data from four or more accelerometers mounted on the vehicle. The acceleration data points were the average of two accelerometer readings. The two accelerometers selected were the floor pan and the left rear seat accelerometers. In the event inaccurate velocity changes of the vehicle were predicted, the best alternative accelerometers were selected. The raw data from all 36 load cells was processed. The raw acceleration data points were filtered according to SAE J211 Standard, with a corner frequency of 18. In earlier analyses by the authors, the barrier data was filtered in the same way as the acceleration data. This provided stiffness data that was nearly linear at crush levels of 250 mm. However, this level of filtering was found to be inappropriate for low levels of crush. Consequently, for this study, the data was filtered according to SAE J211 Standard, with a corner frequency of 90.

The effects of the of filtering on the barrier data are shown in Figure 2. Earlier studies used the 18 corner frequency filter. This study used the 90 corner frequency filter.

It was assumed that the zero time steps provided in the data were accurate, and were identical for the force and acceleration data. Beginning with the zero time step, acceleration data and barrier force data were sampled every 2 ms for 120 ms. The resulting acceleration data and load cell data were the input for subsequent analysis.

In examining the resulting data, several inconsistencies were observed. The most frequent was an initial force on load cells at time zero. In the event the total force at time zero was greater than 10% of the maximum barrier force, the data was rejected. A second problem was the presence of load on cells outside the contact region, or unrealistically high loads on cells inside the contact region. These cases were not rejected in the event the consequence was negligible. Finally, in some cases, the acceleration readings produced a higher or lower delta-V than expected. In the event that the delta-V prediction from the accelerometers up to the time of maximum crush was within 10%, the data was not rejected.

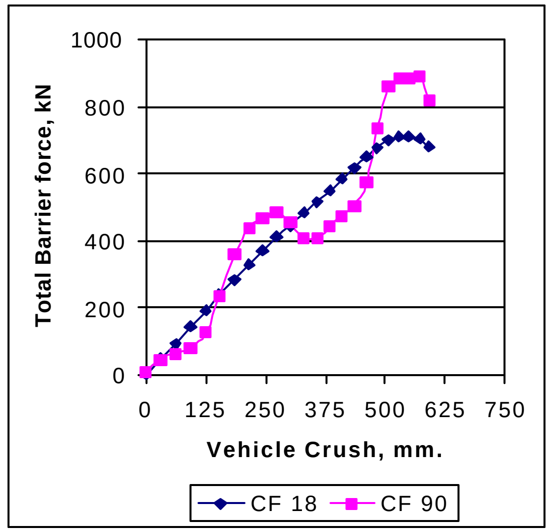

Figure 2. Total Force vs. Crush for 1996 Chevrolet Tahoe Filtered with Corner Frequencies of 18 and 90

STIFFNESS AND CENTER OF FORCE CALCULATIONS

To quantify the height of the structural loading, a center of impact force was calculated for three columns of cells. The left column contained load cells in Groups 1 and 4, the center column Groups 2 and 5, and the right column Groups 3 and 6. In addition, the height of the center of force for the total loading was calculated. For each grouping, the force on each row of cells was assumed to be uniformly distributed. The center of force in the vertical direction was determined by calculating the magnitude and height of a single force that would be required to resist the sum of the forces and moments generated by the forces on the four rows of load cells. First, the force (F) that was required to resist the sum of the load cell forces from rows A, B, C, and D was determined by static equilibrium. The height of force F was then found by applying moment equilibrium to the barrier forces and moment arms. The height H was defined as the Center of Force. The center of force calculation was made for the entire rows of load cells as well as for the left third, the center third, and the right third of the rows. Sample calculations for the center of force for the 36 load cells are shown in Table 1.

The stiffness was calculated by dividing the force measured by the load cells at a particular time by the calculated vehicle crush at that time. The vehicle crush was determined by double integration of the longitudinal acceleration measured on a structural member close to the vehicle's center of gravity.

Table 1.
Sample Calculation of Height of Center of Force, Test 2211 – 1995 Ford Explorer

Rows	Force, N	Row Height, mm.	Force x Height
D Hi	128,985	861	111×10^6
C Hi	336,652	615	207×10^6
B Lo	104,001	369	39×10^6
A Lo	354	123	$.04 \times 10^6$
Total	569,992		356×10^6

Barrier C of Force (356×10^6)/(569,992) mm. ..625.6
Ground Clearance (mm.) 66.6
Height Above Ground of Force Center, mm. 692.2

COMPATIBILITY MEASUREMENT FOR VEHICLES IN NCAP TESTS

The barrier data for NCAP tests between 1995 and 1999 were reviewed for the suitability of barrier data for the analysis outlined above. Other tests were rejected because complete load cell data was not collected, or because the barrier was different in configuration from that is Figure 1. A total of 48 tests of different makes and models were analyzed and the results are reported in Table 2. This Table shows the vehicle class, the stiffness and the center of force values at 125 mm. of crush.

It may be desirable to assess the compatibility properties at even lower values of crush. However, the properties at low values of crush require a very accurate determination of time zero and an accurate measurement of the forces at low loads. An examination of the data suggested that neither of these factors was sufficiently reliable to merit data analysis at lower values of crush.

In the analysis, the nine columns of load cells are divided into three groups, as described earlier. The groups are the left, center and right columns. In Table 2, CF designate the height in mm.of the center of force. The stiffnesses, SCT, are the total force in Newtons at 125 mm of crush divided by 125 mm.

Figure 3 shows a plot of the center-of-force vs. vehicle stiffness at 125 mm of crush. This plot indicates differences in stiffness and center-of-force for pickups and MPV's when compared to passenger cars. There is considerably more scatter in the data for the vans.

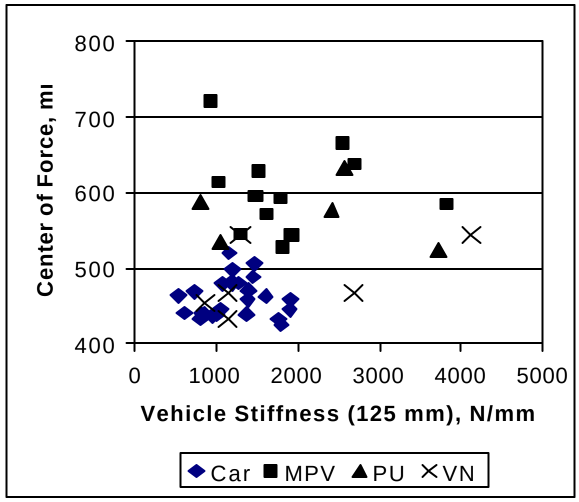

Figure 3. Vehicle Stiffness and COF at 125 mm of Crush

Figure 3 does not adequately indicate the differences in local stiffness across the vehicle. The barrier data indicates large differences in the load concentration from passenger cars vs. light trucks and vans. Comparisons can be made by plotting for each column of load cells the magnitude of the stiffness and the height of the center-of-force. This is done in Figure 4 for the Dodge Neon, and in Figure 5 for the Ford Clubwagon. The plots are for 125 mm of crush. The x-axis designates the load cell row numbers (2L is 2 left, 7R is 7 right). There was no significant load on rows 1L and 9R for the either vehicle.

The Neon data shows that the center-of-force is not only lower, but also the loading is fairly uniformly distributed. The Clubwagon data shows that the center-of-forces are higher and the loads highly concentrated on two of the columns of load cells. For the Clubwagon, the center-of-force is higher in the center than on the two sides.

These two vehicles represent fairly extreme differences. The other light trucks had barrier characteristics generally similar to the Clubwagon.

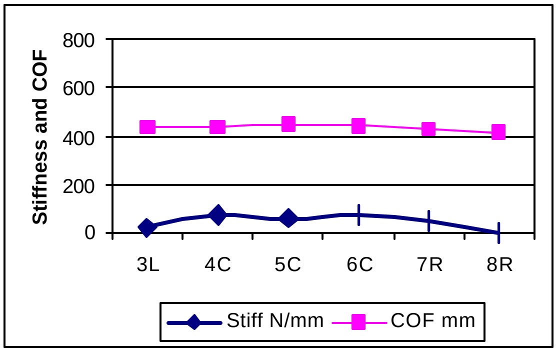

Figure 4. Stiffness and Center-of-Force for Neon Car at 125 mm of Crush

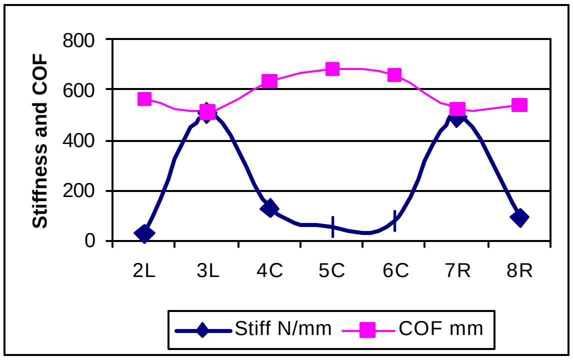

Figure 5. Stiffness and Center-of-Force for Clubwagon Van at 125 mm. of Crush

DISCUSSION

Measurements of geometric and stiffness properties at low values of crush requires accuracy of the load cells at low load values. In addition, it requires precision in the determination of time zero for the acceleration and the barrier data. To date, the barrier data has been used primarily for assessing the maximum loads and the stiffness based on large amounts of crush. Consequently, accuracy at low loads has not been a major concern. If measurements at low loads become important, additional calibration may be required to assure the accuracy of the data.

In many of the tests, the force was concentrated on only two rows of load cells. Additional resolution would be desirable improve the accuracy of the center of force calculation.

The results of the barrier data analysis provide useful insights into the geometry and stiffness of vehicle frontal structure in a barrier crash. A combination of the center of force and the stiffness distribution may be required to define front-to-side compatibility. This would require better quantification of the stiffness variations shown in figures 4 and 5. By developing metrics for geometry and stiffness properties, it may be possible to more precisely quantify vehicle compatibility. The aggressive performance of vehicles in front-to-side collisions may be better understood using metrics of the type developed in this paper.

The proposed metrics need to be evaluated further. The evaluation should include the assessment of a larger number of vehicles and the assignment of the proposed geometry and stiffness compatibility metrics based on barrier crash test data. The resulting metrics should be evaluated by determining the extent to which they explain the differences in vehicle aggressiveness characteristics observed in the on-the-road crash data.

ACKNOWLEDGMENTS

A portion of the research presented in this paper was sponsored by the National Highway Traffic Safety Administration.

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Table 2.

Barrier Data at 125 mm of Crush

Model	***Year***	***Class***	***Wgt***	***CF***	***TS***
Metro	1995	Car	1125	440	847
Mirage	1996	Car	1185	441	610
SL1	1999	Car	1255	434	809
Civic	1999	Car	1259	438	1011
Sephia	1995	Car	1290	438	1372
323-Protégé	1999	Car	1321	445	1049
Neon	1996	Car	1354	439	822
Elantra	1996	Car	1422	458	1386
Cavalier	1995	Car	1433	438	966
626	1999	Car	1459	432	1765
Eclipse	1995	Car	1490	445	1899
Avenger	1995	Car	1516	462	1604
Beetle	1999	Car	1573	425	1801
Mustang	1998	Car	1585	520	1163
Grand Am	1999	Car	1618	506	1468
Stratus	1995	Car	1626	488	1457
Forester	1999	Car	1654	458	1914
Mustang	1996	Car	1700	498	1201
325 I	1995	Car	1717	480	1270
Lumina	1995	Car	1741	469	739
Grand Prix	1997	Car	1753	480	1078
ES300	1996	Car	1759	470	1397
Taurus	1996	Car	1764	482	1190
Intrepid	1999	Car	1770	464	534
Intrigue	1999	Car	1783	480	1191
Sidekick	1995	MPV	1471	544	1922
Cherokee	1995	MPV	1637	629	1515
RAV4	1997	MPV	1642	596	1479
4Runner	1996	MPV	2076	585	3808
Blazer	1997	MPV	2107	546	1299
Gr Cherokee	1999	MPV	2135	665	2547
Explorer	1995	MPV	2206	639	2692
Trooper II	1995	MPV	2232	721	924
M Class	1998	MPV	2277	528	1810
Discovery	1996	MPV	2315	593	1783
Expedition	1999	MPV	2497	572	1621
Tahoe	1996	MPV	2732	615	1033
Ranger	1996	PU	1709	576	2412
S-10	1999	PU	1885	534	1056
Dakota	1997	PU	2015	634	2570
F-150 Pickup	1997	PU	2056	524	3711
C-1500	1996	PU	2163	587	809
Caravan	1996	VN	1934	468	1142
Venture	1996	VN	1946	466	2681
Gr Caravan	1996	VN	2003	453	863
Odyssey	1999	VN	2194	434	1142
Astro	1999	VN	2301	543	1300
Clubwagon	1995	VN	2595	544	4121